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A novel approach for reducing toxic emissions during high temperature processing of electronic waste

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A novel approach is presented to capture some of the potentially toxic elements (PTEs), other particulates and emissions during the heat treatment of e-waste using alumina adsorbents. Waste PCBs from mobile phones were mechanically crushed to sizes less than 1 mm; their thermal degradation was investigated using thermo-gravimetric analysis. Observed weight loss was attributed to the degradation of polymers and the vaporization of organic constituents and volatile metals. The sample assembly containing PCB powder and adsorbent was heat treated at 600 °C for times ranging between 10 and 30 min with air, nitrogen and argon as carrier gases. Weight gains up to ~17% were recorded in the adsorbent thereby indicating the capture of significant amounts of particulates. The highest level of adsorption was observed in N_2 atmosphere for small particle sizes of alumina. SEM/EDS results on the adsorbent indicated the presence of Cu, Pb, Si, Mg and C. These studies were supplemented with ICP-OES analysis to determine the extent of various species captured as a function of operating parameters. This innovative, low-cost approach has the potential for utilization in the informal sector and/or developing countries, and could play a significant role in reducing toxic emissions from e-waste processing towards environmentally safe limits.

1. Introduction

Regular induction of new designs and rapid technology upgrades in consumer electronics such as mobile phones, computers, TVs and notebooks, followed by intense global marketing is causing the early obsolescence of a large number of electronic items. Electronic waste (e-waste) is one of the fastest growing solid waste streams in the world; in 2014, nearly 41.8 million metric tonnes of obsolete equipment was generated worldwide (Baldé et al., 2015). Both formal and informal sectors are engaged around the world in recycling such e-waste to recover precious and other metals (up to 40–70% value) (Cui and Roven, 2011; Marques et al., 2013). Waste printed circuit boards (PCBs), the central component of electronic devices, contain significant amounts of hazardous/-toxic constituents in addition to a variety of metals, ceramics and polymers. Various hazards associated with e-waste arise when the equipment reaches its end-of-life and is disassembled, and later recycled, incinerated or deposited in a landfill. Discarded e-devices contain elements that can pose a risk to human health and the environment over extended exposure.

With a current recycling rate of only ~10–18%, most of the discarded electronic equipment is either trashed in landfills or incinerated (APC, 2000; Pinto, 2008). Recycling waste PCBs in an environmentally sustainable manner is a challenging issue. Various e-waste recycling methods used in the informal sector include manual dismantling, open burning, chipping, melting, burning wires to recover copper, acid & cyanide salt leaching, and other inadequate metallurgical treatments (Dwivedy and Mittal, 2012; Leung et al., 2015; Li et al., 2015). These activities can release dust particles loaded with potentially toxic elements (PTEs) and flame retardants into the atmosphere that may re-deposit near the emission site, or be transported over long distances depending on the particulate size (de Oliveira et al., 2012; Sepúlveda et al., 2010). The term PTE is collectively used to represent elements such as Zn, Cu, Ni, Cd, Pb, Hg, Cr, Mo, Se and As, known to accumulate, persist and contaminate soils and the environment; and could have a detrimental influence on human health (Xie et al., 2012). Poor

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recycling techniques, especially in developing countries, generate high levels of environmental pollution that affect both the ecosystems and the health of population living near the main recycling areas (Song and Li, 2014; Zhang et al., 2012).

The environmental fate of particulates, fumes and ashes from burning activities is similar to that of dismantling dust, with toxic pollutants such as dioxins, furans, lead and other metals ending up in soil, ground water and the atmosphere (Stenvall et al., 2013; Wang and Xu, 2014; Widmer et al., 2005). During controlled pyrolysis of waste PCBs in the temperature range 750–1550 °C, Rajarao et al. (2014) observed that more than 90% of the lead present was lost as emissions during heating to 750 °C itself; several other metals showed a similar behaviour. The loss of hazardous/other metals and PTEs as emissions is a serious issue, especially during uncontrolled/open burning of waste, causing significant environmental pollution (Breivik et al., 2014; Fromme et al., 2016; Ren et al., 2014). A number of studies have been reported in the literature on the capture of hazardous metals such as Pb, Cd and Zn from various incineration processes (Abanades et al., 2002; Sørum et al., 2004; Uberoi and Shadman, 1991). While high temperatures have routinely been used to treat different types of wastes (Kim, 2001; San Miguel et al., 2002; Velghe et al., 2011), not much attention has been paid towards capturing released particulate matter or on limiting associated environmental contamination. Most e-waste recycling activities have been focussed primarily on the recovery of valuable and other materials from e-waste (Hagelüken, 2006; Cui and Roven, 2011), with limited attention paid to the environmental sustainability of the processes used (Bhutta et al., 2011; Bridgen et al., 2005).

Along with the generation of harmful emissions during e-waste processing, the release of toxic ingredients over an extended period can pose serious threats to the health and the environment (Tanskanen, 2013). Ellamparuthy et al. (2017) have investigated the recycling of waste PCBs at high temperatures (up to 1500 °C) using thermal plasma and have characterized airborne particulates in the exhaust gas captured in gas-bag filters. Particulate sizes were found to range between 3 and 200 μm; a high concentration of carbon was detected along with oxides, metals and other impurities. Results showed clear evidence for the presence of metals such as Cu, Al, Fe, Sn, Zn, Ni; hazardous metals such as Pb, Sb, As, Cd, and several other elements in trace amounts. To capture such metals, PTEs and other harmful emissions, extensive gas cleaning systems/filters have become integral components of e-waste recycling in developed countries (Chiang and Lin, 2014; López-Fonseca et al., 2010); these are however rarely used in the informal sector or in developing countries due to inadequate legislation, cost factors and technological issues.

Over the past several years, our group has been working actively on developing optimal e-waste recycling approaches, including the recovery of copper (Cayumil et al., 2014, 2017), concentrating precious metals in small volumes (Cayumil et al., 2015), the generation of novel carbons, fibers and foams from waste PCBs (Khanna et al., 2015; Sahajwalla et al., 2015), etc. During our e-waste recycling studies, we have developed a novel approach to capture some of the toxic gases/particulates, metal fumes or dusts generated during the heat treatment of e-waste. In this study, we report an in-depth investigation on capturing metal particulates present in the exhaust gas using alumina adsorbents. Alumina adsorbents have previously been used to remove heavy metal ions from waste water; this approach offered simplicity of approach, low costs, high removal efficiency and operational convenience (Afkhami et al., 2010). Along with detailed results on captured particulates, optimal operating conditions were also determined towards enhancing particulate removal and lowering the environmental pollution associated with high temperature processing of waste PCBs. The key challenge here was to develop an environmentally sustainable approach for processing e-waste that could be implemented in developing and transitional economies in a cost-effective and energy-efficient manner.

2. Experimental

Waste PCBs used in this study were taken from a range of end of life mobile phones. These were crushed and mechanically size reduced to powder sizes of less than 1 mm. As a first step, the thermal degradation behaviour of these powders was investigated using thermo-gravimetric analysis (TGA-DTG) using nitrogen as carrier gas (flow rate: 0.2 L/min). TGA investigations were carried out to establish the thermal region of maximum gas release and associated weight loss. Significant amounts of gas release were expected due to polymer degradation in waste PCBs; the release of these gases may cause fine particles to become airborne and be carried away with the flowing N_2 gas. Secondly, the vapour pressures of some volatile metals could become significant at high operating temperatures of the furnace resulting in their loss in the vapour phase. TGA results on the system are shown in Fig. 1. A 20% weight loss was observed in the temperature range of 300–400 °C with a further gradual weight loss up to 6% in the temperature range between 400 °C and 700 °C. This gradual weight loss continued up to 1200 °C without much change in slope. It was therefore decided to carry out gas adsorption studies at 600 °C as most of the gas release is likely to have occurred by this stage. This temperature lies just beyond the degradation temperature of polymers and the associated release of volatiles from waste PCBs. It is important to note that temperatures ≥800 °C are more appropriate for the recycling of waste PCBs as the generation of harmful dioxins/-furans generated from e-waste becomes negligible at these temperatures (Mckay, 2002). However lower temperatures were chosen in this study to maximise the release of metal particulates along with gases generated during polymer degradation.

Alumina was used as an adsorbent to capture fine particulates released during thermal degradation of waste PCB powders. Alumina has previously been used for the adsorption & removal of metallic phases from aqueous solutions (Afkhami et al., 2010; Hua et al., 2012). Several factors however need to be taken into account while choosing an appropriate adsorbent for the gas phase. These include adsorbent stability at high temperatures, the rate and capacity for adsorption, low toxicity and easy disposal (Uberoi and Shadman, 1990). Alumina was chosen as the adsorbent medium in this investigation due to its highly porous granular nature, surface area and capacity for adsorption (Gupta et al., 2011). In addition, it has high thermal stability, and does not react or decompose at the temperatures of this investigation. Alumina surface is also known to be hydrophilic in nature and has low adsorption affinity for organic compounds (Afkhami et al., 2010); these adsorbents will therefore be suitable for metal adsorption even in the presence of organic compounds released during polymer degradation.

Specific features of the alumina adsorbent used in this investigation have been summarised in Table 1. These basic characteristics also include the maximum level of impurities present initially and the solubility of the adsorbent in a range of solvents. Three commercially available particle sizes of alumina were used in this investigation with an aim to identify optimal adsorbent characteristics. Alumina powders were dried in an oven at 150 °C for 24 h prior to their use. The trapping and the capture of particulates from waste PCBs was investigated at 600 °C using a range of carrier gases and heating times. A schematic representation of the experimental arrangement is presented in Fig. 2. A quartz tube furnace was used for the heat treatment of waste PCBs; the furnace was heated at the rate of 10 °C/min to 600 °C, maintained there

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